Density fluctuations in different types of solar wind flow at 1 AU and comparison to Doppler scintillation measurements near the Sun

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Abstract

Density fluctuations based on ISEE 3 plasma measurements in the range 10 minutes to 1 hour have been investigated in the following solar wind flows at 1 AU: coronal hole, interstream, plasma sheet, coronal mass ejection, and interaction region. The, ISEE 3 results reinforce the interpretation of large-scale variations in density fluctuations observed by Doppler scintillation measurements inside 0.2 AU. The highest absolute and relative density fluctuations occur ahead of and in the plasma from coronal mass ejections, with the maximum values occurring between the associated interplanetary shocks and the driver gas. For the quasi-stationary solar wind, density and relative density fluctuations are highest in the plasma sheet in which the heliospheric current sheet is embedded, and lowest in the high-speed coronal hole flow. Superposed epoch analysis shows that the region of enhanced density fluctuations and its abrupt boundaries, observed in the vicinity of the heliospheric current sheet near the Sun persists to 1 AU, providing further support for the filamentary nature of the extensions of coronal streamers. The results of this study confirm the advantages of density fluctuations over density, both as tracers of solar wind flows with differing origins at the Sun and as detectors of propagating interplanetary disturbances.

Brief Report

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INTRODUCTION

Plasma density fluctuations spanning an extensive range of spatial and temporal scales arc ubiquitous in the solar wind. Direct in-situ measurements of density fluctuations between 0.3 and -50 AU have been complemented by indirect measurements of the inner heliospshere inside 1 AU deduced from radio scintillation observations, a phrase used here to collectively represent all those measurements that observe the effects of density fluctuations on the propagation of radio signals, e.g., intensity scintillation (often termed IPS for interplanetary scintillation), phase/Doppler scintillation, angular and spectral broadening, etc.). Radio scintillation observations were first carried out with natural radio sources and later also with spacecraft radio signals [*Hewish*, 1972; *Woo, 1993a]*. Small-scale density fluctuations in the acceleration region of the solar wind were probed by angular broadening observations even before the existence of the solar wind was confirmed [see e.g., *Newkirk*, 1967]. Although density fluctuations have received considerable attention in both observational and theoretical studies [*Hewish*, 1972; *Cronyn*, 1972; *Neugebauer et al., 1978; Coles*, 1978; *Woo and Armstrong, 1979; Montgomery et al., 1987; Armstrong et al., 1990; Marsch and Tu, 1990; Marsch*, 1991; *Coles* et *al., 1991; Roberts and Goldstein,* 1991; *Zank and Matthaeus, 1992; Bavassano, 1994],* not all aspects of their origin and nature arc yet fully understood.

In addition to characterizing the properties of density fluctuations, radio scintillation and scattering measurements are useful for probing and tracking large scale solar wind features manifesting enhancements in density fluctuations. These enhancements can be either of solar origin, such as propagating interplanetary disturbances [*Rickett, 1975; Woo and Armstrong, 198 1; Tappin et al., 1983; Watanabe and Schwenn, 1989],* or internally generated in the interplanetary medium, as in the case of fluctuations at the leading edges of high-speed streams where the fast wind overtakes the slower plasma in its path [*Anathakrishnan et al., 1980; Tappin et al., 1984].*

Recent studies based on Doppler scintillation measurements near the Sun before evolution with heliocentric distance has a chance to develop reveal that the quasi-stationary solar wind is organized by the large-scale coronal magnetic field in such a way that near the neutral line (heliospheric current sheet), where the coronal magnetic fields arc predominantly closed and the solar wind is slow, density fluctuations are high, while far from the neutral line, they arc conspicuous] y low [*Woo and Gazis*, *1993; Wood al.*, 1994*a,b,c*]. The enhanced density fluctuations overlying the neutral line are of coronal origin, represent the interplanetary manifestation of the heliospheric current sheet, and arc the extensions of coronal streamers. By the time the quasi-stationary flow reaches a heliocentric distance of 0.3AU (near the lower limit of in-situ measurements), it has evolved to a state distinguished more by enhanced density fluctuations on the leading edges of the high-speed streams, consistent with meter wavelength IPS measurements beyond 0.5 AU [*Anathakrishnan et al.*, 1980; *Tappin et al.*, *1984]*.

In this paper we arc also interested in relative density fluctuations. In the interpretation of lPS data, it is often assumed that the fractional density fluctuations ($\sigma N/N$) is constant, so that enhanced scintillation is an indicator of enhanced density [*Houminer and Hewish*, 1974; *Ananthakrishnan et al.*, 1980; *Tappin*, 1986; *Woo and Gazis*, *1994a]*. More recently, combined observations of mean density and density fluctuations indicate that this is not the case in the near-solar plasma [Woo *et al.*, 1994*b,c*].

The purpose of this paper is to usc in-situ, 1 -AU observations of the density and fractional density fluctuations and their relation to other plasma parameters to test for consistency with the identification of solar wind structures and their evolution with solar distance as deduced from radio scintillation data.

DATA ANALYSIS

The study is based on analysis of S-minute averages of solar-wind parameters observed by ISEE 3 between August 1978 and February, 1980. ISEE-3 data are useful for such a study because of the spacecraft's location near the Sun-Earth L1 point and the long duration of nearly gap-free data acquisition at a constant cadence. It was a period of increasing solar activity that allowed the observation of flow from both coronal holes and coronal mass ejections. The plasma and field instrumentation have been described by *Bame et al. [1978]* and by *Frandsen et al. [1978]*, respectively.

In a previous study (with other objectives), *Neugebauer and Alexander* [1991] identified a number of intervals when the solar wind observed by ISEE 3 could be reasonably confidently assigned to one or another type of flow, For the quasi-stationary solar wind, the types of flow considered were coronal holes (CH), the high density plasma sheet (PS) around the heliospheric current sheet, and low-speed, interstream plasma (1 S). Transient flows from coronal mass ejections (CMEs) were identified on the basis of a list of times of counterstreaming suprathermal electrons compiled by Gosling *et al. [1987]* and/or the detection of enhanced helium abundance. The start and stop times of each of the intervals used is given in *Neugebauer and Alexander [1991]* and further information is given in [*Neugebauer*, 1992]. One should note that a few of the results of the present study are guaranteed by the criteria used to select the intervals for study; based on earlier observations of coronal hole flows by *Bame* et *al. [1977]* , a low value of σN (but not $\sigma N/N$) was one of the criteria used to select CH intervals, while high N was onc of the identifiers of PS intervals. An additional type of flow included in the present study is that of interaction regions (IR) between interplanetary shocks and the leading edges of the CME driver gas which follow them. A set of IR intervals was compiled from *Gosling et* al's [1987] list of counterstreaming electron events and the time of observation of any interplanetary shocks that preceded them.

Motivated by recent Doppler scintillation results indicating enhanced density fluctuations interpreted as filamentary or flux tube organization at the heliospheric current sheet inside 0.1 AU [*Woo et al.*, 1994c], we have also undertaken a superposed epoch study of density fluctuations centered on heliospheric current sheet (HCS) crossings. The selected HCS crossings correspond to the more clearly defined events presented by *Bin-ton et al. [1994].*

The study is based on hour-by-hour variations in the 5-minute averages of the ISEE-3 data. The 5-minute lower limit corresponds to the plasma instrument cycle time. Ion charge density $(N_p + 2N_\alpha)$ is used for equivalence to the electron density, since the ion data were generally more reliable than the electron data. For each hour of data included in one of the categories discussed above (i.e., CH, PS, IS, CME, or IR) the average density, $<N>$, the standard deviation from the average density for the n points (n=12) within the hour, $\sigma_N = \left[\sum_{i=1}^{n}(N_i - <N>)^2/(n-1)\right]^{1/2}$, and the relative level of the, fluctuations, $\sigma_N / <N>$, were calculated. The standard deviation therefore represents fluctuations with periods between 10 minutes and 1 hour. The results for all of the hours within each type of solar wind flow are displayed as histograms in Figure 1. As expected, the level of density variation is lowest in coronal holes, and highest in interaction regions where the plasma is being compressed. CMEs also show relatively high fluctuation levels, presumably resulting from the fine structure of their source in the corona. Although the plasma sheet data show fairly modest density fluctuation levels in the range 10 min to 1 hour, the spread in the density hourly averages indicates larger variations on time scales greater than an hour and from one event to another.

Table 1 summarizes the above results. The table lists the average values over the histograms plotted in Figure 1, i.e., the average of the $<N>$ values, the average standard deviation for each type of solar wind flow, and the average relative fluctuation level. Note that the average $<\sigma_N/<N>>$ is not exactly the same as <aN>/<<N>>. At 1 AU, the highest values of $\sigma_N/\langle N\rangle$ are found in the sheaths or interaction regions behind interplanetary shocks.

In Figure 2, a superposed epoch analysis of 18 *HCS* crossing events is presented for the interval ±3 days either side of the boundary epoch. Again, the parameters are calculated for each hour period of data so that all of the 18 ±3-day intervals arc represented in hour] y bins; the values falling in each bin are then averaged over the 18 events, Similar superposed epoch studies of solar wind N, speed V, and temperature T, have previously been presented [e.g., *Borrini et al., 1981]*, but we consider the density fluctuations in this way for the first time.

Near the Sun, the HCS is located in the dense, low-speed wind associated with the coronal streamer belt, which is surrounded by higher speed flows [e.g., *Gosling et al., 198* 1]. As the solar wind structure evolves with increasing distance, the compression ridge on the leading edge of the following high-speed stream gradually overtakes the HCS, causing the high fields seen just after the zero epoch. The velocity and field profiles show that, on the average for these 18 events, the leading edge of the following high speed stream has just passed over the HCS at the time it was observed. The density profile is narrower and less asymmetric than the field profile because of the intrinsic high density of the heliospheric plasma sheet. At 1 AU, there is a broad spike in σ_N at zero epoch, but it probably has contributions from both leading-edge compression and intrinsic variability of solar origin. It is, therefore, not surprising that the regions of enhanced density fluctuations observed closer to the Sun by scintillation measurements are narrower (1 -2° wide) than at 1 AU, as is further discussed below.

D1SCUSS1ON

The frequency band of the ISEE 3 density fluctuations investigated in this paper corresponds to spatial scales larger than those observed by 1 PS measurements, which are restricted to scale sizes smaller than the Fresnel size. On the other hand, Doppler scintillation has the ability to observe the full range of density fluctuations, and measurements closer to the ISEE 3 spatial and temporal scales (of periods 20s to 3 min and 20 min to 5 hr) have been studied [Woo, 1993; *Woo and Gazis*, 1993; *Woo et al.*, 1994*a,b,c*]. The ISH33 density fluctuations at 1 AU exhibit many of the general features observed by these Doppler scintillation measurements near the Sun.

Density fluctuations deduced from Doppler scintillation measurements show two distinct plasma regions in the vicinity of the Sun: 'slow wind' near the neutral line where both density fluctuations and the variation of density fluctuations are high, and 'fast wind' far from the neutral line where both density fluctuations and the variation of density fluctuations are low [Woo *and Gazis*, 1993, 1994]. The ISEE 3 measurements at 1 AU reinforce these near-Sun results, as low and high values of σN and $\sigma_{\sigma N}$ (see Table 1) are found in coronal hole and plasma sheet flows, respectively. As revealed by combined time-delay and time-delay scintillation measurements of fast and slow wind near the Sun [*Woo et al.*, 1994*b*], $\sigma N/N$ has likewise been found to be correspondingly low and high in coronal hole and plasma sheet flows, respectively. The approximate factor of two contrast between density fluctuations in coronal hole and plasma sheet flows is consistent with the contrast of the spatial wavenumber spectra of density fluctuations in high and low speed flows observed by in-situ Helios measurements near 1 AU [*Marsch and Tu*, 1991].

The enhanced density fluctuations observed at the HCS by ISEE 3 are similar to those observed by Doppler scintillation near the Sun in the extensions of coronal streamers, These near-Sun scintillation results show boundaries of density fluctuations which are more abrupt than those of density itself, and provide evidence for coherent spatial structure reflecting filamentary or flux tube organization in the coronal streamer extension [Woo *et al.*, 1994*c*]. Discussions of the filamentary nature of the streamer belt plasma near 1 AU have been previously published (e.g., [*Crooker et al., 1993;*

Winterhalter et al., 1993]). Furthermore, evolution of this signature of the coronal streamer extension is manifested by the gradual erosion of the enhancement of density fluctuations with increasing heliocentric distance accompanied by the broadening of the region of enhanced fluctuations. The 1-AU ISEE 3 plasma measurements have been compared and found to be consistent with Ulysses Doppler scintillation measurements of the HCS at 0.9 AU [Woo *et al.*, 1994*c*]. That the boundaries of the enhanced density fluctuations, especially those west of the HCS and least affected by the fast streams, arc more abrupt than those of enhanced density in the superposed epoch analysis of sector boundary crossing events, indicates that at least part of the filamentary structure observed in the extensions of coronal streamers near the Sun survives to 1 AU.

Levels of both density and density fluctuations are lowest in coronal hole flow. For the sake of comparison, we display in Fig. 3 the enhancements in levels of N, σN and $\sigma N/N$ over those of coronal hole flow for other types of solar wind. These results confirm what has been generally observed in the comparison of time delay and time delay scintillation measurements of the HCS [Woo *et al.*, 1994b], and the comparison of Doppler scintillation and in-situ plasma measurements of interplanetary shocks *[Woo and Schwenn, 1991]* – that the contrast in σN between different solar wind flows is not only high, but higher than that of density. Closer to the Sun and before evolution with solar wind expansion, contrasts arc even greater in coronal mass ejections *[Woo and Armstrong, 1981; Woo, 1993]* and heliospheric current sheets [Woo *et al.*, 1994c], leading to prominent signatures in scintillation measurements of both types of solar wind flow.

According to Table 1, the highest values of σN and $\sigma\sigma N$ are those of interaction regions. These results reaffirm the significant advantage due to increased sensitivity of scintillation measurements (sensing density fluctuations) over white-light coronagraph measurements (sensing density) for detecting interplanetary shocks that precede fast moving CMEs [Woo *et al., 1982].*

CONCLUSIONS

Motivated by the large-scale variations of density fluctuations observed by scintillation measurements near the Sun, we have investigated density fluctuations in different types of solar wind flow at 1 AU using in-situ ISEE 3 plasma measurements. Although evolution has already taken place during passage from the Sun to 1 AU, characterization of the different solar wind flows is facilitated by the availability of more complete information on fields and particles, This study is limited to fluctuations slower than 10 rein, but the general solar wind behavior observed in scintillation measurements near the Sun extends over a fairly broad range of fluctuation frequency.

While less extreme because of evolution with heliocentric distance, the variation of density fluctuations observed at 1 AU confirms that deduced from scintillation measurements closer to the Sun, Density and relative density fluctuations arc highest in CME events, with the maximum values occurring in the sheaths just behind interplanetary shocks. For the quasi-stationary solar wind, density and relative density fluctuations arc highest in the. plasma sheet in which the heliospheric current sheet is embedded, and lowest in the high-speed corona] hole flow. The fact that density fluctuations are higher in plasma sheet than in coronal hole flow is consistent with the implications for heating and acceleration of the solar wind reached by *Neugebauer and Alexander [1991]* based on observations of tangential (TD) and rotational (RD) discontinuities. The plasma density often jumps across TDs but is nearly constant across RDs. Neugebauer and Alexander found the rate of occurrence of TDs to be higher in plasma sheet flow than in either interstream or coronal hole. flow, Enhanced density fluctuations associated with leading edges of corotating high speed streams have not been included in this study because the 1978-1980 interval covers the high activity portion of the solar cycle when few low latitude high speed streams from coronal holes were present. Superposed epoch analysis of heliospheric current sheets also shows that the regions of enhanced density fluctuations along with their abrupt boundaries observed in the vicinity of the neutral line near the Sun persist to 1 AU, providing further support for the filamentary nature of the extensions of coronal streamers. Finally, the results of this paper confirm the advantages of using density fluctuations rather than density as tracers of solar wind flows with differing origins on the Sun and as detectors of propagating interplanetary disturbances.

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Table 1 Mean density and density fluctuation parameters.

Characterization	No. of hours	$\langle\langle N\rangle\rangle$ (cm^{-3})	$\langle\sigma_N\rangle$ (cm^{-3})	average $\sigma_N / \langle N\rangle$	σ of σ_N
Coronal Holes	186	5.13	0.20	0.039	0.12
Interstream	143	8.12	0.44	0.056	0.46
Plasma Sheet	5"?	19,62	1.50	0.082	1.51
CME	174	7.93	0.97	0.129	1.56
Interaction regions	146	16.24	2.61	0.152	4.61

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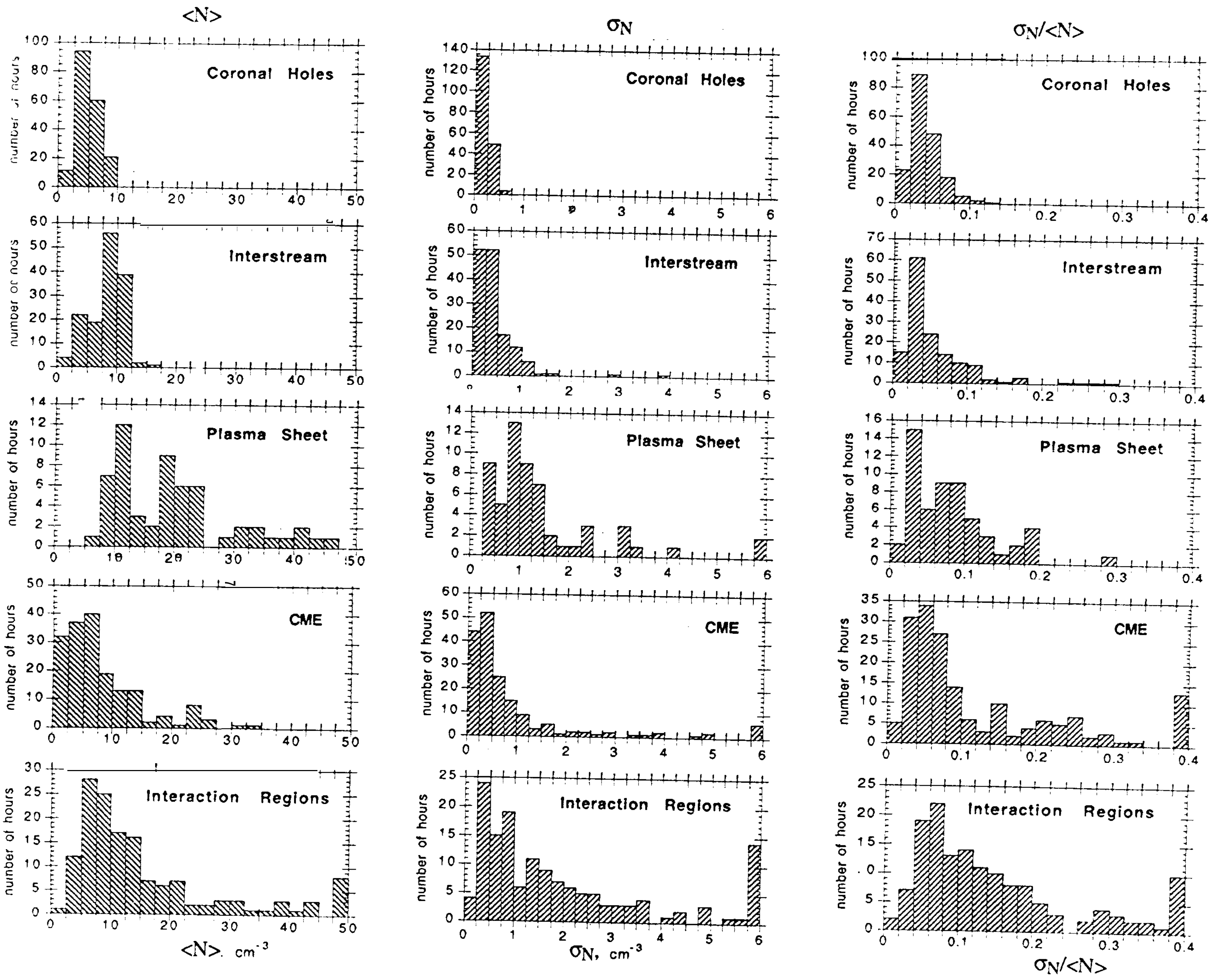
Figure Captions

Fig. 1. Comparison of hourly values of <N>, σ_N, and $\sigma_N/\langle N \rangle$ found in solar wind flow from coronal holes, and in interstream, plasma sheet, CME, and interaction regions. The observations are from ISEE-3 at 1 AU.

Fig. 2. Superposed epoch study of 1 AU ISEE-3 observations ±3 days either side of the heliospheric current sheet. 18 such intervals are averaged in this analysis.

Fig. 3. Ratios of mean density, density fluctuations, and fractional density fluctuations for the various types of flow (in Fig. 1 and Table 1) to the values seen in flow from coronal holes.



<N>
σN
σN/<N>
Coronal Holes
Interstream
Plasma Sheet
CME
Interaction Regions
number of hours
<N>, cm⁻³
σN, cm⁻³

Fig. 1

HELIOSPHERIC CURRENT SHEET: Superposed Epoch

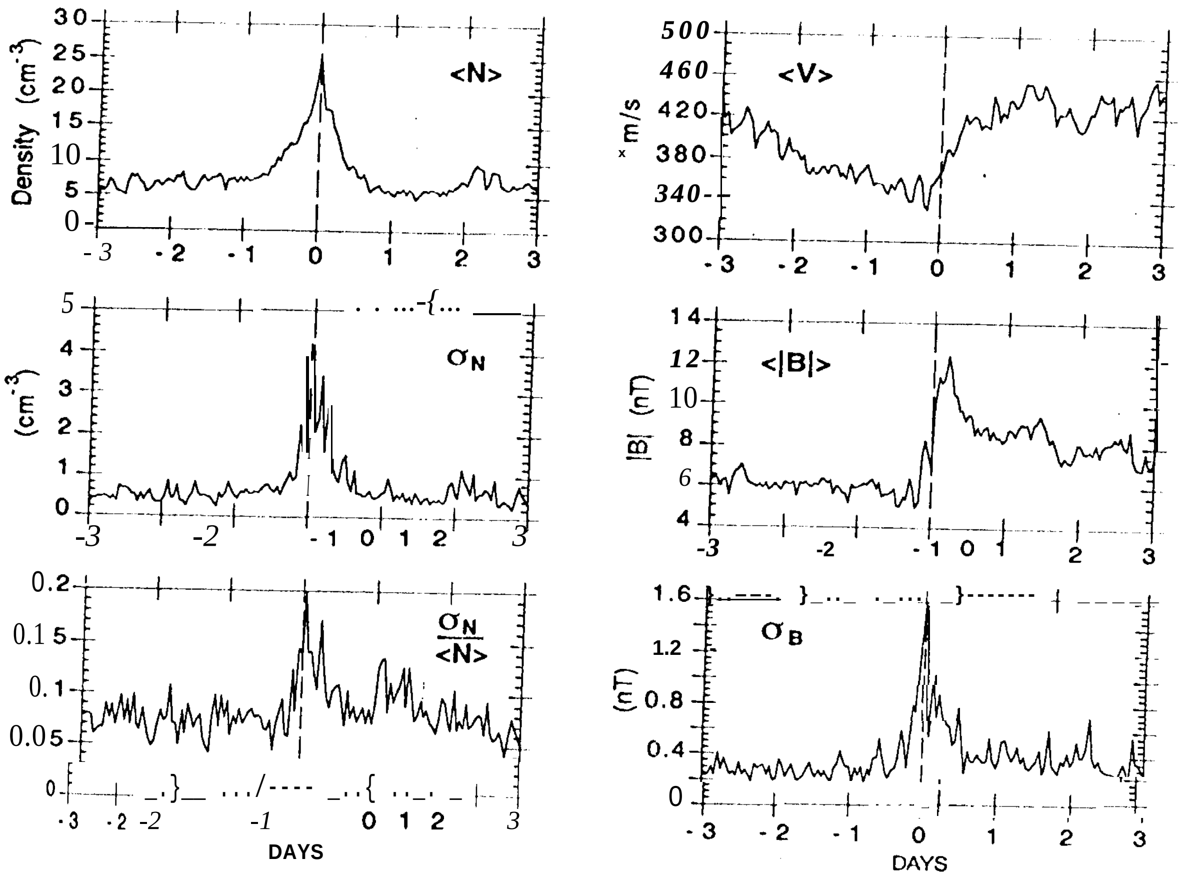
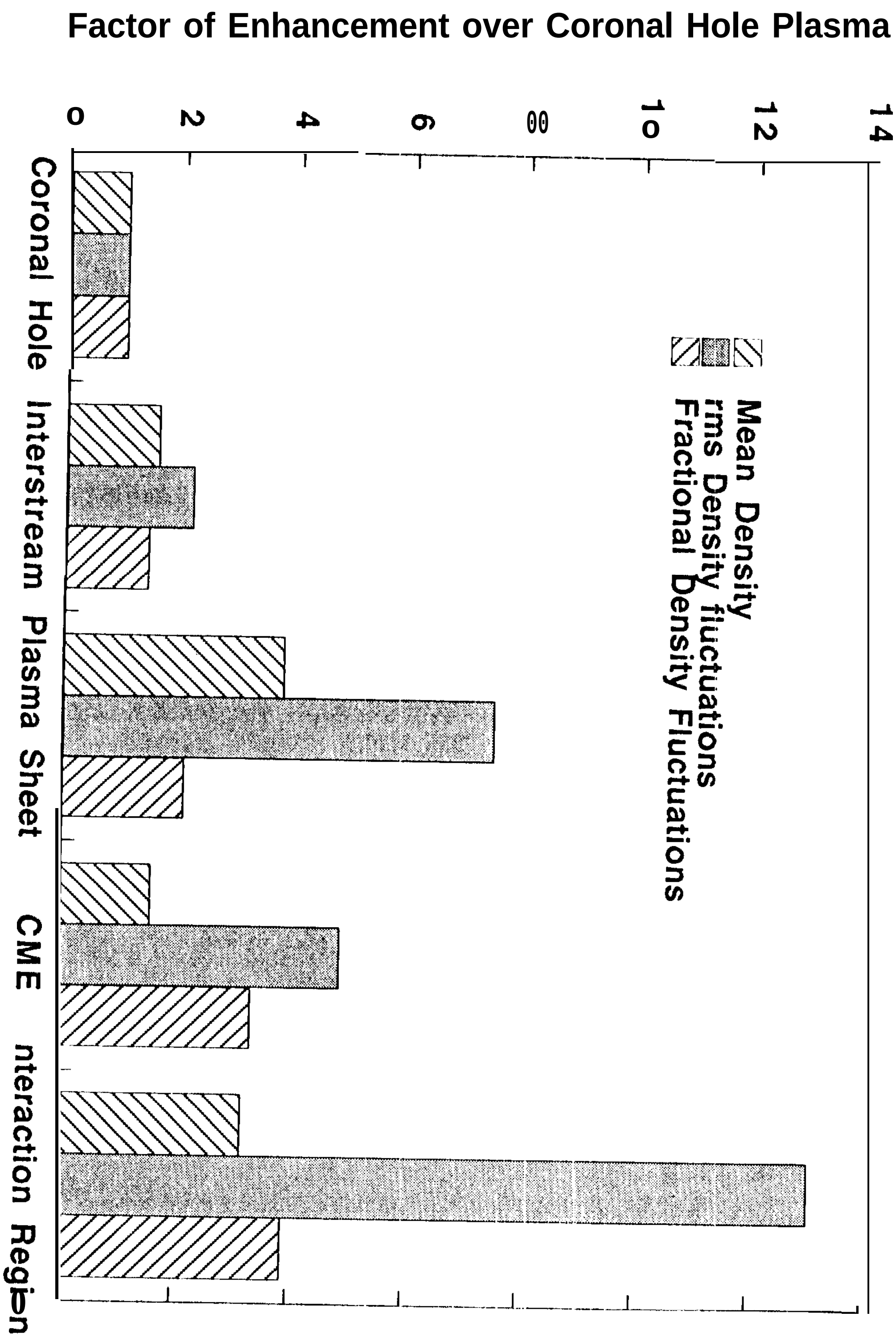


Fig. 2.

Fig. 3


Factor of Enhancement over Coronal Hole Plasma
0
2
4
6
8
10
12
14
Mean Density
rms Density fluctuations
Fractional Density Fluctuations
Coronal Hole
Interstream
Plasma Sheet
CME
Interaction Region